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TITLE: INTERFEROMETRIC STUDIES OF PLASMA-DENSITY FLUCTUATIONS IN ZT-40M, USING TIME-DELAYED CORRELATION TECHNIQUES

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Interferometric Studies of Plasma-Density Fluctuations in ZT-40M, Using Time-Delayed Correlation Techniques

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Abstract: Density fluctuations in a reversed-field pinch have been studied using multichord CO_2-laser interferometry. Both non-periodic and quasi-periodic oscillations have been observed. The latter are m = 0 and m = 1 and remain toroidally localized until the final stage of the discharge, when the m = 0 oscillation becomes toroidally coherent (with n = 1).

1. Introduction

This paper reports observations of plasma density fluctuations in the ZT-40M[1] reversed-field pinch (RFP). An array[2] of eight interferometer chords at one toroidal location (ϕ) measures the fluctuations' poloidal symmetry (that is, m), or, in the case of transient disturbances, the poloidal propagation characteristics. A supplementary interferometer chord, separated toroidally from the others by $R\Delta\phi$ = 1.8 m, measures the toroidal propagation characteristics.

The observed density fluctuations may be divided into two broad classes. First, there are the more numerous non-periodic disturbances, consisting of impulsive perturbations which grow, saturate, and decay, and which do not recur in any obvious manner. Second, there are less numerous, quasi-periodic oscillations, of either m = 0 or m = 1 poloidal symmetry, occurring in sustained bursts lasting up to ~ 100 periods. The m = 0 period τ_o is typically in the range $20 < \tau_o < 200$ μs, while the m = 1 oscillations are faster ($5 < \tau_1 < 30$ μs).

The impulsive, non-periodic density disturbances are expected to launch familiar normal modes of a magnetized plasma, which by carrying energy away from the source disturbance could allow it to spread and to decay. Preliminary observations in the edge region of the ZT-40M discharge indicate that ion-acoustic waves play this role,[3] and that such observation of ion-acoustic propagation might be diagnostically useful by providing a determination of the sound speed. [The fast wave could in principle also communicate impulsive plasma density disturbances, but the present apparatus[2] on ZT-40M is too slow to resolve time-delays associated with the Alfvén speed ($V_A \gtrsim 5 \times 10^7$ cm/s).]

The observed quasi-periodic oscillations are poorly understood. If they were simply RFP versions of familiar relaxation (sawtooth) or rotating magnetic island (Mirnov) oscillations observed on tokamaks, then toroidal coherence (that is, a well-defined toroidal mode number, n) would be expected. Cross-correlations between the eight-chord array and the supplementary chord reveal that, with a few exceptions, the quasi-periodic oscillations on ZT-40M are toroidally isolated and do not cohere over an arc of $R\Delta\phi$ = 1.8 m.

2. Apparatus

Both the eight-chord[2] and single-chord interferometers are a heterodyne design[4] with quadrature phase detection,[5] and are illuminated by waveguide CO_2 lasers (λ = 10.6 μm). The instrumental resolution (quantization in analog-to-digital conversion) is $\simeq 4 \times 10^{-4}$ fringes, while the noise in the bandwidth 15-500 kHz is $\simeq 2 \times 10^{-4}$ fringes (rms). The sampling rate is 1 or 4 MHz, and the analog bandwidth is DC-500 kHz. The interferometric phase ϕ_j (on chord j) is digitally filtered with a high-pass transmission $T(\omega) = 1-e^{-(\omega/\omega_{co})^2}$, giving the high-pass phase $\tilde{\phi}_j$.

3. Non-Periodic Density Fluctuations

Digitally-filtered phase data from the eight-chord array is used to compute an ensemble-averaged, time-delayed covariance between vertical chords at major radii R_j and R_k:

$$P(R_j,\ R_k,\ \Delta t) \equiv \frac{1}{Nt_{av}} \sum_{n=1}^{N} \int_{t_n}^{t_n+t_{av}} \tilde{\phi}_j(t_n)\tilde{\phi}_k(t_n + \Delta t)dt_n \ . \qquad (1)$$

Here N is the number of consecutive, identical discharges being used in the average, t_{av} is the averaging time within a discharge, and t_n is the time variable within the n^{th} discharge. In the correlation to follow, N = 14 shots, and t_{av} = 1.6 ms. Because the disturbances rapidly decay as they propagate, a graph simply of $P(R_j, R_k, \Delta t)$ versus Δt suppresses the propagation effects. A more convenient way to examine propagation is to compute the renormalized correlation:

$$C^*_{\Delta t}(R_j,\ R_k) \equiv P(R_j,\ R_k,\ \Delta t)/P(R_j,\ R_k,\ \Delta t^*) \ . \qquad (2)$$

Here Δt^* is the delay which maximizes the covariance for separation $\Delta R = R_j - R_k$.

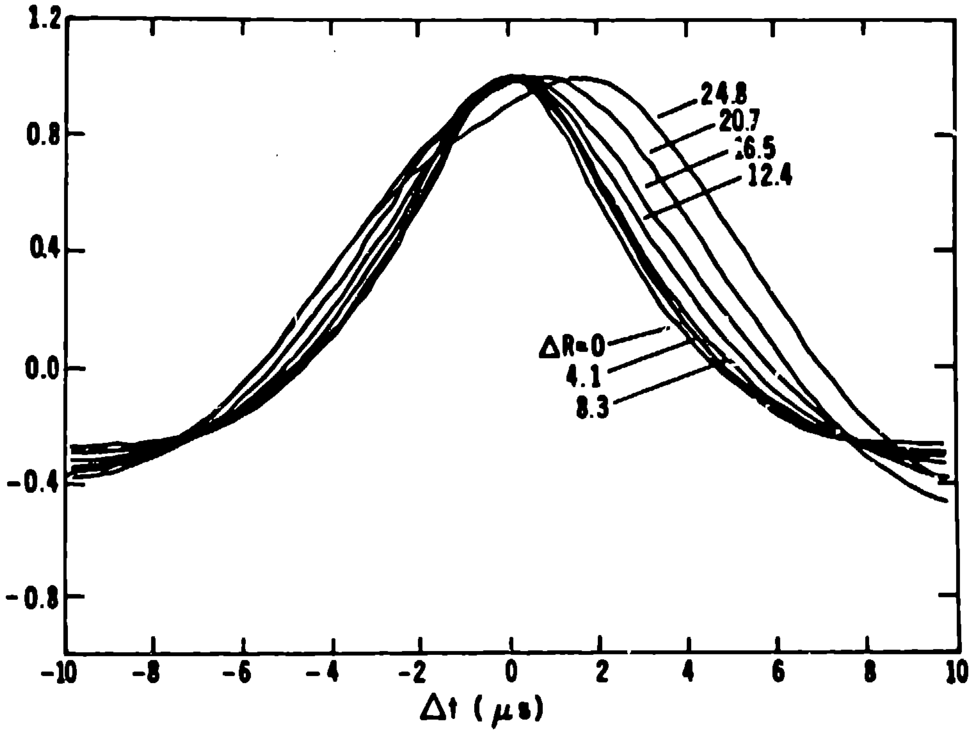

Fig. 1. Renormalized correlations [see Eq. (2)] versus time delay. The separation (ΔR) in cm is noted.

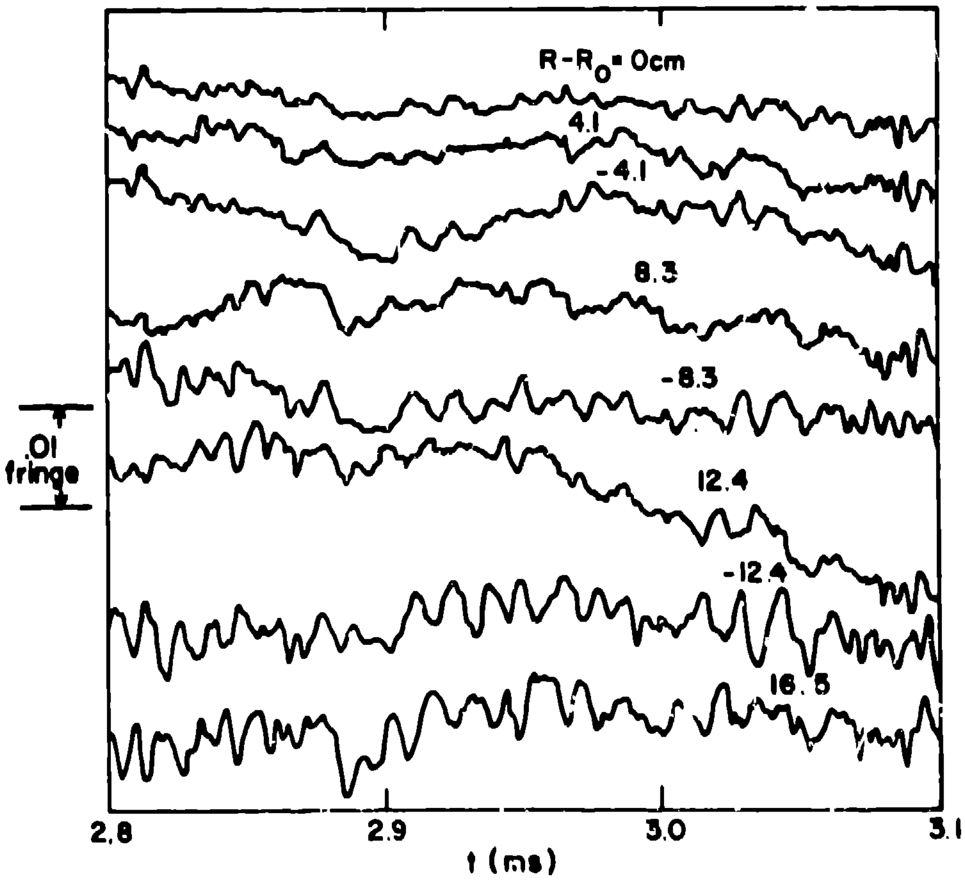

Fig. 2. Interferometric phase versus time during an m = 1 burst. Impact parameter ($R-R_0$) in cm is noted for each signal.

Figure 1 shows $C^{*}_{\Delta t}(R_j,R_k)$ for R_j-R_o = 12.4 cm and for $R_k = R_j-\Delta R$. (The filter cutoff is $\omega_{co} = 1 \times 10^5 s^{-1}$). The increasing breadth (in Δt) of the correlations for larger separation (ΔR) forms the basis for determining a pro. ation speed. Further analysis[3,6] determines a major-radial speed $V_R \approx 2 \times 10^6$cm/s, which has been shown to be most likely caused by sound waves near the field-reversal surface of the pinch.[6]

4. Quasi-Periodic Density Fluctuations

The observed quasi-periodic fluctuations are exclusively $m = 0$ or $m = 1$. The $m = 1$ oscillations have not been observed to propagate a quarter of the major perimeter ($R\Delta\phi$ = 1.8 m). Instead, $m = 1$ quasi-periodic oscillations frequently occur simultaneously at both the eight-chord array and the supplementary chord, but with different frequencies, so that the disturbances can not be coherent all the way around the torus. A radial magnetic field probe[7] in the liner-shell interspace near the eight-chord array indicates that the $m = 1$ oscillations are primarily in-out (along R) linear perturbations, that is, actually a coherent sum of $m = \pm 1$. A typical $m = 1$ burst is shown in Fig. 2. The disturbances are strongest at $R-R_o$ = −12.4 cm and +16.5 cm (and out of phase) and are less evident at smaller impact parameter, as expected for $m = 1$.

The observed $m = 0$ oscillations similarly fail to cohere over $R\Delta\phi$ = 1.8 m, except during the last ~ 2 ms of the discharge. In this stage, the $m = 0$ features begin to precess toroidally (opposite to I_ϕ) at a speed $V_\phi \approx 0.7\text{-}1.2 \times 10^7$cm/s. In the final $\simeq$ 1 ms of the discharge, the precession is observed to become resonant; that is, $V_\phi \tau_o = 2\pi R$, so that a resonant $n = 1$, $m = 0$ mode is achieved. It is not yet clear whether the pinch termination and the $m = 0$ oscillation's enhanced toroidal coherence are related causally.

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